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In studying any particular irrigation system, the first step is identifying the extent of water pollution problems, which is usually done by analyzing inflow-outflow data for the irrigated area. Then, the sources of these pollutants must be established, which may require extensive field investigations. The next step is a cost-effectiveness analysis, where the cost of implementing a technology to various levels is compared against its effectiveness for improving water quality. These cost-effectiveness relations can then be assessed in an optimizational format to arrive at the least cost combination for achieving a desired level of water pollution control.

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COST-EFFECTIVE STRATEGIES FOR ALLEVIATING WATER QUALITY DEGRADATION FROM IRRIGATED AGRICULTURE*

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ABSTRACT

We are now moving from a concern for maximizing crop production on a single plot, or farm, to evaluating large-area agricultural systems in order tom aximize economic gains under the constraint of minimizing pollution resulting from return flows. To accomplish this objective may require a change in the physical system, but much can be accomplished by more efficient use of materials (e.g., water, fertilizers, pesticides, and herbicides).

In studying any particular irrigation system, the first step is identifying the extent of water pollution problems, which is usually done by analyzing inflow-outflow data for the irrigated area. Then, the sources of these pollutants must be established, which may require extensive field investigations. The next step is a cost-effectiveness analysis, where the cost of implementing a technology to various levels is compared against its effectiveness for improving water quality. These cost-effectiveness relations can then be assessed in an optimizational format to arrive at the least cost combination for achieving a desired level of water pollution control.

These concepts are illustrated for three irrigation systems in the western United States; namely, Yakima Valley, Wellton-Mohawk Irrigation and Drainage District and Grand Valley.

Even after taking into account the "site specific" nature of irrigated agriculture in general, and these case studies in particular, the most

* Politiques à coût réduit pour empêchen la dégradation de la qualité' des laux par l'irrigation agricole

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cost-effective solutions for reducing water quality problems from irrigated agriculture will likely be improved on-farm water management practices.

RESUME

On est maintenant passé du souci de maximisation de la production agricole sur un lopin isolé, ou une ferme, à celui de l'évaluation de systèmes importants à fin de maximisation des gains économiques sous la contrainte de pollution minimum par les eaux usées. Pour accomplir le dessein, il est peut-être nécessaire de changer le système physique mais on peut accomplir beaucoup par un usage plus efficace des matériaux (eau, engrais, pesticide et herbicide, etc.).

Dans toute étude d'un système particulier d'irrigation, on doit d'abord identifier l'importance de la pollution, ce qui est accompli d'ordinaire par l'analyse des données d'entrées et de sorties du périmètre irrigué. Ensuite on doit établir les origines de la pollution, étape qui peut nécessiter une analyse sur le terrain. Enfin on doit comparer le coût de mise en oeuvre d'une technique à différents niveaux par rapport à son efficacité en termes d'amélioration de la qualité de l'eau. On peut alors quantifier dans un cadre d'optimisation sa relation de coût pour dériver une combinaison de coût minimum, pour un niveau de contrôle de la pollution donné.

On a illustré ces idées sur trois systèmes d'irrigation dans l'ouest des Etats-Unis notamment la Yakima Valley, d'irrigation et de drainage de Wellton-Mohawk et la Grand Valley.

Même si l'on prend en compte la situation particulière de chaque profit d'irrigation agricole en général, et pour les cas étudiés en particulier, l'amélioration des pratiques de gestion au niveau de la ferme demeure le moyen le plus probable de réduction des problèmes de qualité des eaux à moindres frais.

INTRODUCTION

We are now moving from a concern for maximizing crop production on a single plot, or farm, to evaluating large area agricultural systems in order to maximize economic gains under the constraint of minimizing pollution resulting from return flows. To accomplish this objective may require a change in the physical system (e.g., waste treatment, recycling, canal lining, land leveling, trickle irrigation, etc.), but much can be accomplished by more efficient use of materials (e.g., water, pesticider, herbicides, and fertilizers).

To predict the effects of agricultural practices upon the quality of water returning to groundwater reservoirs and/or rivers requires the addition of subroutines to the models describing the quantity and quality of flows moving through the surface and groundwater systems in a river basin. One of the subroutines must describe the agricultural water delivery system (precipitation and/or irrigation canal) in terms of the quantity, quality, and time history of water application. Next, a differentiation must be made

between the water that infiltrates into the soil and the water that occurs as surface runoff from the land.

One of the more difficult models to develop and verify for a large area is the movement of water and consequent quality changes from the ground surface to the water table. The dynamic soil-plant-water model must be capable of describing both saturated and unsaturated moisture movement, water and nutrient uptake by plants, evaporation, microbiological transformations, ion movement, and ion exchange.

Once the quantity and quality of flows reaching the ground water have been evaluated, it then becomes necessary to predict: (1) changes with time in groundwater recharge, groundwater table elevation, and quality; and (2) changes with time in groundwater return flows (both quantity and quality) to the river system. The above predictions would also be made to evaluate proposed changes in agricultural practices, with particular emphasis being placed upon evaluating the cost-effectiveness of various technologies (and associated alternative policies) in minimizing pollution from irrigation return flows while taking into consideration crop yields.

The process for developing cost-effective strategies for minimizing water quality degradation from irrigated agriculture will be described based upon three recent case studies. The case study areas are Yakima Valley, Wellton-Mohawk Irrigation and Drainage District, and Grand Valley (Figure 1).

YAKIMA VALLEY

INTRODUCTION

The Yakima Valley has a total area of 15,700 sq. km. (6,062 sq. mi.) and occupies the north-central part of the State of Washington. The Yakima River and its tributaries drain the valley. The river heads near the crest of the Cascade Range, northeast of Mount Rainier and flows for 290 km. (180 miles) in a generally southeasterly direction to its confluence with the Columbia River near Richland. The total annual flow leaving the Valley under natural conditions would be approximately 4,420 million cubic meters (3,580,000 acre feet). The actual flow is 2,890 million cubic meters (2,340,000 acre feet). The average annual irrigation diversions within the basin are 2,920 million cubic meters (2,365,000 acre feet) of which 1,410 million cubic meters (1,140,000 acre feet) are consumed and 120 million cubic meters (100,000 acre feet) are diverted from the basin.

The climate varies from desert conditions in the lower valley to a moist alpine type in the higher mountains. The irrigated area of the upper valley receives from 250 to 380 mm. (10 to 15 inches) of precipitation per year, while the lower valley receives less than 250 mm (10 inches).

Agriculture is the primary economic activity. Yakima is a center for processing both fruit and vegetable crops grown in the adjacent valleys. There is a limited number of lumber and wood product plants.

The Yakima Valley is now one of the most extensively irrigated areas in the united States, having six storage dams, five diversion dams, two hydroelectric plants, six major governmental irrigation projects plus

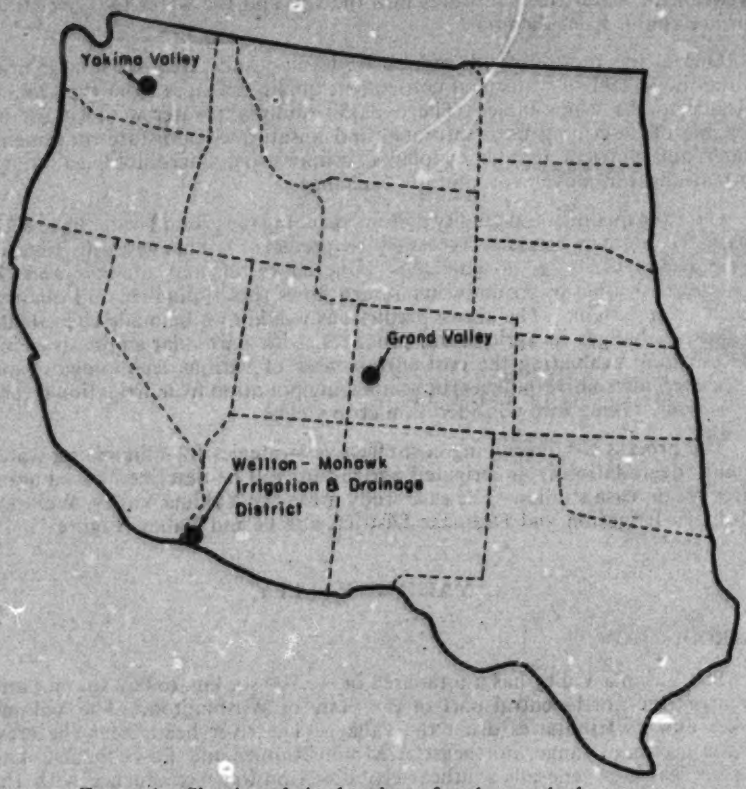

FIGURE 1 : Showing relative locations of study areas in the western United States of America

numerous small, private irrigation systems and districts. The total area served by irrigation facilities in the valley is approximately 204,000 ha (505,000 acres) of which 168,000 ha (416,000 acres) are served by governmental projects. Water for the remaining irrigable land is supplied through Warren Act contracts and by individuals diverting from small streams. About 7,300 ha (18,000 acres) are irrigated by groundwater.

Approximately 80 per cent of the irrigated area of the valley is watered by furrow or flood irrigation methods. The remainder is sprinkler irrigated except fot a few hundred acres of trickle irrigation. There is currently a marked trend towards sprinkler systems.

With the advent of irrigation in the valley, the quality of water in the Yakima River and its tributaries has declined. Some of the degradation is directly due to irrigation return flows, while further deterioration is associated with fruit processing plant and other agricultural and industrial enterprises attracted to the valley by the strong irrigated agricultural base.

In the upper reaches of the valley, water quality is virtually unimpaired. Although mineralization increases more than fourfold in going from the headwaters to the mouth, the water still remains in the low salinity class and is suitable for reuse as irrigation water. The main effect of irrigation activities is increased concentrations of suspended sediment, phosphates and nitrates.

Suspended solids in return flows settle and interfere with drain design flow capacity and cause wear of pumps and sprinklers. Where discharged to the river, they settle behind diversion structures and require periodic removal. Associated with the sediment is adsorbed phosphate which frequently reaches levels in the lower river above the potential algal bloom limiting concentration. Similarly, nitrogen levels, which are a consequence of the percolation of irrigation water applied in excess of crop needs, greatly exceed the potential algal bloom limiting concentrations in the lower river. Heavy growths of plankton and higher forms of aquatic life are consequently found in the river as it flows through the lower valley. The photosynthesis and respirational activities of these organisms cause a wide diurnal fluctuation in several water quality parameters including dissolved oxygen, *p*H and alkalinity.

COST-EFFECTIVENESS OF SEDIMENT AND NITROGEN REDUCTION

Gossett and Whittlesey (1976) have utilized available data from studies in Yakima Valley regarding the cost of various on-farm technological alternatives for achieving different levels of sediment and nitrogen reduction in determining cost-effectiveness. The primary purpose of their analysis was to evaluate the effects of various pollution abatement policy alternatives upon net farm revenue, crop production, and pollution levels.

Sediment pollution abatement

Gossett and Whittlesey (1976) concluded that sediment pollution of irrigation return flow can be minimized by adopting more capital-intensive irrigation systems. However, where capital is limiting, tests of policies reveal that the most efficient way to reduce sediment yields is to simultaneously employ additional labor with better irrigation management and to substitute wheat for row crops.

Regardless of the policy implemented, sediment reduction beyond 50% to 60 per cent (Figure 2) became quite costly to the producer when financial physical conditions prohibited adoption of other irrigation systems. Under such circumstances, reduction of sediment loss beyond 60 per cent caused significant losses in income and crop production. When physical conditions permitted, sediment could be eliminated from return flow by the tail water reuse system, which involved an $18/acre capital investment at 1973 prices. However, with field slopes greater than 2 per cent and coarse textured soils, this system was not feasible, and sprinkler irriation was required to eliminate sediment outflow. In this case capital investment required would be about $160/acre. (The analysis by Gossett and Whittlesey, 1976, did not include trickle irrigation.)

Nitrogen pollution abatement

In the short run, where capital is not invested in irrigation equipment, the three most economical farm adjustments for controlling nitrogen leaching

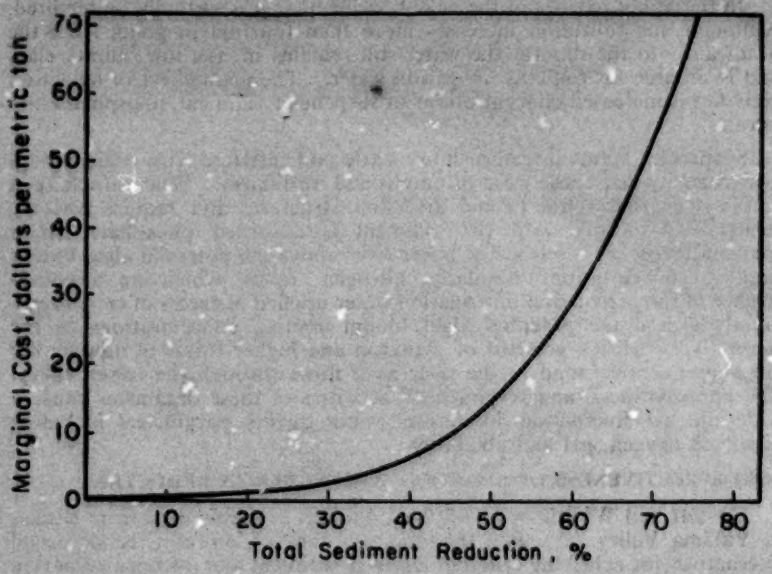

FIGURE 2 : Marginal cost of sediment pollution abatement

were improving the existing irrigation system, reducing nitrogen application, and substituting alfalfa for wheat and sugar beets.

Among the feasible policies, constraining nitrogen use and taxing nitrogen fertlizer were the most effective in causing desired adjustments. Either policy could cause a 50 per cent reduction in nitrogen residuals. However, taxing fertilizer caused large producer costs, including a 20 per cent reduction in crop production.

Constraining or taxing water use were also potentially cost-effective policies from society's view, although somewhat less than the fertilizer-directed policies. The water-directed policies curtailed nitrogen use only by reducing crop acreage as water became limiting. The tax on water was very costly for the producer, even for small nitrogen waste reductions. In the long run, where capital investment was possible, the feasible policies maintained the same relative cost-effectiveness. Constraining the use of water or fertilizer caused nitrogen waste reductions of 40 per cent, with practically no loss in farm income or crop production after proper adjustments in the irrigation system were made. Waste reductions beyond 60 per cent (40 per cent nitrogen residual in Figure 3) became increasingly costly to the producer. A 75 per cent nitrogen reduction (25 per cent nitrogen residual in Figure 3) required an average capital investment of $ 215/ha. The loss in crop production was about 30 per cent.

Conclusions

The study by Gossett and Whittlesey (1976) indicates that substantial improvements in irrigation return flow quality may be possible without undue

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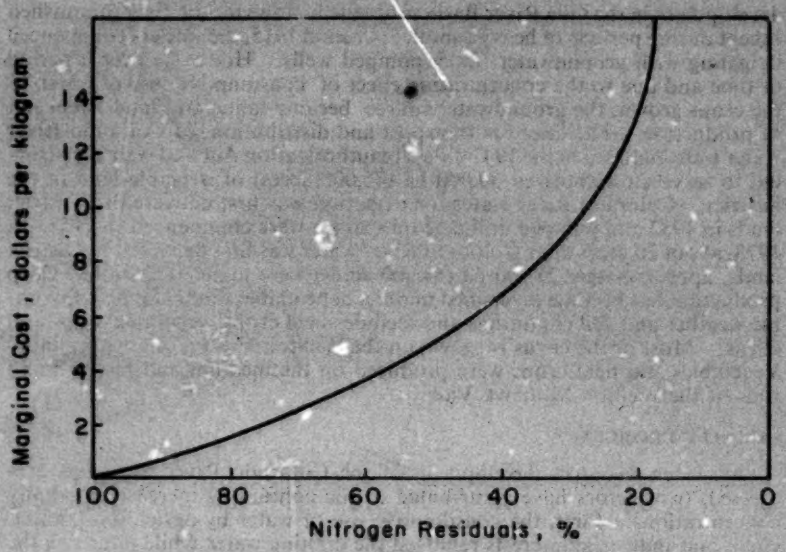

FIGURE 3 : Marginal cost of nitrogen pollution abatement

hardship on farmers in the Yakima Basin. For many years, nitrogen fertilizer and water have been used inefficiently as inexpensive inputs. Relatively small constraints or surcharges on these inputs will cause improved irrigation practices and, consequently, more efficient water and nitrogen use. Resulting residual reductions would be about 25 per cent and 50 per cent for nitrogen and sediment, respectively, with negligible losses in farm income or crop production. These residual reductions would be possible with no additional capital investment.

Probably, if water or nitrogen become limiting, the producer will invest additional capital in irrigation equipment rather than to employ addtitional manpower. This trend is already apparent in irrigated areas where labor is limiting. A capital investment of $45/ha in a tailwater reuse system that doubles as a sediment settling basin could potentially reduce nitrogen losses by 30 per cent and eliminate sediment. This adjustment could actually increase the producer's net income. With this irrigation system, the residual reduction of 50 per cent seems to be possible with minor income or crop losses. However, reductions beyond 50 per cent would require adoption of either an automatic reuse system or solid-set sprinklers if severe income and crop losses are to be avoided. The capital investments would be $360/ha for the automatic reuse system and $1615/ha for the solid-set sprinkler system (Gossett and Whittlesey, 1976).

WELLTON-MOHAWK IRRIGATION AND DRAINAGE DISTRICT

INTRODUCTION

The history of agricultural development in the Wellton-Mohawk area includes early irrigation with water from the Gila River. As upstream

development in the Gila River Basin proceeded, flows in the river diminished except during periods of heavy runoff. Around 1915, the settlers commenced irrigating with groundwater from pumped wells. However, over a period of time and due to the concentrating effect of consumptive use of water by the crops grown, the groundwater source became saline and lands went out of production. Facilities for transport and distribution of Colorado River water were included in the 1947 Gila Reauthorization Act and were constructed to serve an authorized 30,000 ha (75,000 acres) of irrigable land in the District. Colorado River water for irrigation was first delivered to District lands in 1952 and pumped drainage operations were commenced in 1957. In 1973, about 20 years after Colorado River water was first delivered to District lands, approximately 25,600 ha (64,000 acres) were under irrigation. Crop production has become diversified under a dependable water supply, favorable weather and soil conditions and includes field crops, vegetable crops and ctirus. Most of the citrus is grown on the Wellton Mesa along with alfalfa. Vegetables and field crops were produced on the medium and fine textured soils of the Wellton-Mohawk Valley.

SALINITY PROBLEM

As water resources development of the Colorado River Basin has progressed, two factors have contributed to the continuing increase in salinity concentrations. First, the consumptive use of water by agricultural, municipal, and industrial interests removed the diluting water while returning the salts to the river system, thereby "concentrating" the salts in downstream flows. Second, some activities, such as the leaching of saline agricultuaral lands, resulted in "salt pickup" that returned more salts to the river than had been diverted. Changes in water quality along the river were noted as early as 1903, and the seven States in the Colorado River Basin have wrestled with the problem for years. The effect of the salinity is very costly. Loss to the regional economy along the 2,240-km river due to poor quality of water was estimated at about $53 million in 1973. By the year 2000, losses could reach about $124 million per year in the U.S.A. if water resource development continues and no salinity reduction measures are implemented (Bessler and Maletic, 1975).

The increasing salinity levels in the lower Colorado River became an international situation when the quantity of flows reaching Mexicali Valley were reduced as a result of additonal storage reservoirs in the Upper Basin, combined with highly saline pumped drainage being discharged into the lower reaches of the Colorado River by the Wellton-Mohawk Irrigation and Drainage District. At first, the Wellton-Mohawk drainage water was pumped into the Gila River channel and discharged to the Colorado River. The drainage water initially was quite saline, averaging about 6,000 mg/l of total dissolved solids. The concrete-lined Wellton-Mohawk Main Conveyance Channel was constructed in the early 1960's to carry the drainage water from the wells. These waters were then discharged to the Gila River near its confluence with the Colorado River and thence flowed via the Colorado River and were delivered to Mexico at the northerly International Boundary as part of the flows under the 1944 Water Treaty.

The average annual salinity of the water delivered to Mexico at the northerly International Boundary increased in 1961 from about 800 mg/l to nearly 1,400 mg/l, and in 1962 to nearly 1,500 mg/l of total dissolved

solids. This increase was due largely from the discharge to the river of drainage waters from the Wellton-Mohawk District, coupled with the marked decrease in the same years in excess flows reaching Mexico.

The increase in salinity created an international situation, and on March 16, 1962, the President of the United States and the President of the Republic of Mexico agreed that it was urgent to find a mutually satisfactory solution. Minute No. 218 and Minute No. 241 of the International Boundary and Water Commission were interim solutions that included provisions for discharging a portion of the Wellton-Mohawk return flows to the Colorado River below Mexico's diversion structure. The effect of these agreements, coupled with improvements in the quality of the Wellton-Mohawk return flows, was to reduce the average salinity of Colorado River water made available to Mexico to 1,140 mg/l of total dissolved solids for the year ending June 30, 1973.

In their historic meeting in Washington, D.C., in June 1972, President Nixon pledged to President Echeverria that he would appoint an official representative to find a permanent and definitive solution to the salinity problem. President Nixon appointed Herbert Brownell, Jr., former U.S. Attorney General, as his special representative. Mr. Brownell was assisted by an interagency task force. Brownell's key proposal was that the United States build a plant to desalt a major portion of the Wellton-Mohawk drainage flow, and that the reject brine from the plant not be charged as part of the treaty allotment to Mexico, thus eliminating completely the influence ot fhe Wellton-Mohawk drainage on the salinity level agreed to in Minute No. 242 of the International Boundary and Water Commission, United States and Mexico.

Minute No. 242 requires that the water delivered to Mexico upstream from Morelos Dam have an annual average salinity of no more than 115 mg/l of total dissolved solids over the annual average salinity of Colorado River water arriving at Imperial Dam. The agreement commits the United States to extend the concrete-lined Wellton-Mohawk bypass drain to the Arizona-Sonora International Boundary. From there, Mexico will extend it, with U.S. funding, 59 km to the Santa Clara Slough in Mexico near the Gulf of California. The extension will carry reject brine from the desalting plant near Yuma and, when the plant is not in operation, drainage water from the Wellton-Mohawk farmlands. The entire drain—extending from the Wellton-Mohawk Irrigation and Drainage District to the Santa Clara Slough—will be 210 km long. Another feature of the project is protective and regulatory pumping. Each country has agreed to limit pumping of groundwater in its territory within 8 km (5 miles) of the Arizona-Sonora boundary near San Luis to 197 million cubic meters (160,000 acre-feet) annually. By this agreement, Mexico will not expand its pumping in this area, and the United States may increase its pumping to the amounts specified.

COST-EFFECTIVENESS ASSESSMENT

An interagency Advisory Committee on Irrigation Efficiency, Wellton-Mohawk Irrigation and Drainage District, prepared a report in 1974 which provided an assessment of measures for improving irrigation efficiencies. This assessment study was undertaken to analyze irrigation efficiencies in the Wellton-Mohawk Irrigation and Drainage District and recommend measures

required to improve water management so that drainage return flows can be reduced. An installation to desalt Wellton-Mohawk drainage return flows has been authorized under Title I of Public Law 93-320 as a means of meeting the salinity differential stated in Minute No. 242 of the International Boundary and Water Commission. If the volume of Wellton-Mohawk drainage is reduced, desalting costs will also be reduced. The results reported below are taken from the report of the Advisory Committee.

Data on water use, crops and yields were used to determine on-farm irrigation efficiencies for 1970, 1971, and 1972. These data reflect average irrigation efficiencies of about 33 per cent on the mesa farms and 65 per cent on the valley farms for those years. The average irrigation efficiency District-wide was about 56 per cent. About 264 million cubic meters (214,000 acre-feet) annually of return flows are associated with 56 per cent irrigation efficiency.

The Advisory Committee estimated that irrigation efficiencies could be increased by improved water management practices. A further increase in irrigation efficiency could be attained by improvement of the on-farm irrigation systems. Four program levels were developed to evaluate the cost of on-farm improvements and their effect on reducing return flows.

The program levels considered and their cost, irrigation efficiency, and estimated return flow associated with each are presented in Table 1.

TABLE I

Program levels and costs. (*Source: Advisory Committee on Irrigation Efficiency—Wellton-Mohawk Irrigation and Drainage District*)

Program Level	*Efficiency*	*Return flow*	*Federal cost*	
			*Installation**	*Annual equivalent***
	(Per cent)	($10^6 m^3$/yr)	($ million)	($ million)
1	64	206	1·65	0·10
2	69	181	5·53	0·33
3	72	168	7·51	0·45
4	82	116	11·15	0·67

* Based on 75 per cent Federal cost sharing for permanent on-farm irrigation improvements plus program expenditures for technical assistance, irrigation management services, and research and demonstration.

** Interest at 5-5/8 per cent for 50 years.

A concurrent study of desalting costs was undertaken to evaluate the relationship between desalting costs and volumes of return flow. In the study, the total range of probable desalting costs was explored. Design level parameters, such as plant recovery rates, TDS, and ionic water composition changes were examined over a broad range of drain flows to determine general cost sensitivities. Desalting cost variability for selected levels of irrigation efficiency, river salinity levels and long-term aquifer changes were also examined. The significant results of the cost study are presented in Table 2. Although the desalting costs shown are based on several assumptions for the various program levels, the Federal investment to improve irrigation efficiency appears highly justified.

TABLE II

Desalting costs for selected program levels. (*Source: Advisory Committee on Irrigation Efficiency—Wellton-Mohawk Irrigation and Drainage District*)

Level	*Efficiency*	*Return flow*	*Federal cost*	
			*Capital**	*Annual equivalent***
	(Per cent)	($10^6 m^3$/yr)	($ million)	($ million)
Base case	62	216	93·7	15·0
1	64	206	91·1	14·5
2	69	181	84·2	13·1
3	72	168	80·9	12·4

* For a representative, reverse osmosis membrane desalting process.

** Includes interest at 5-5/8 per cent for 50 years on installation cost and all operation, maintenance, replacement, and power costs.

The Advisory Committee concluded that the highest level capable of achievement prior to the desalting plant startup is a desirable goal. This is identified as Program Level 3 and has a cost-effective ratio of 6 : 1. Program Level 4, although projected as effective in reducing desalting costs is believed not practical of achievement in the time period required. Program Level 3 would require that the following on-farm improvements be implemented : (1) install on-farm structural features to improve gravity irrigation systems on 19,800 acres (8,000 hectares); (2) convert to pressure systems on about 4,000 acres (1,600 hectares) of mesa land for use on citrus; and (3) continue the limited use of portable sprinkler pressure systems to germinate lettuce. The calculated return flow for Program Level 3 of 136,000 acre-feet (168 million cubic meters) per year is a resonable objective. Irrigation efficiencies of 64 per cent on the mesa lands and 74 per cent on the valley lands are

projected. The average District-wide irrigation efficiency would be 72 per cent.

If measures under Program Level 3 are fully implemented and if the effectiveness of these improvements increase irrigation efficiencies as projected, return flows should eventually reduce to 168 million cubic meters per year. However, there are uncertainties in reaching this objective, which include : (1) imprecision in the calculations of return flow quantities: (2) reservations that not all projected on-farm improvements will be fully implemented prior to the plant startup date or that the measures will be as effective in increasing irrigation efficiencies as estimated : and (3) changes in cropping patterns. The Advisory Committee is highly confident that return flows due to drainage requirements will be reduced to 216 million cubic meters (175,000 acre-feet) per year and considers it reasonable to expect that return flows will be reduced to 150,000 acre-feet (185 million cubic meters) per year.

The Colorado River Basin Salinity Control Act (PL93-320, June 24, 1974) stipulated that the irrigable acreage in the District should be reduced by approximately 4,000 hectares to preclude additional development that might increase drainage return flows and to insure that water use does not exceed the District's Colorado River allocation.

GRAND VALLEY

INFLOW-OUTFLOW ANALYSIS

The increasing salinity problem in the Colorado River Basin has necessitated the collection and analysis of data on water and salt flows in order to evaluate the contributions from various sources. Although several interested governmental agencies have conducted short-term studies in the basin, the primary source of data is the stream monitoring system of the U. S. Geological Survey. One of the most comprehensive efforts to summarize and analyze these data was made by Iorns, Hembree, and Oakland (1965) for the period between 1914 and 1957 and adjusted to the 1957 conditions. The study was inclusive of the entire Upper Colorado River Basin, but for the purposes of this paper only the section dealing with the Grand Valley area has been extracted. The total salt loading to the Colorado River from the Grand Valley averaged about 680,000 metric tons annually during the period.

The 1963-1967 water years were selected by the Colorado River Board of California (1970) in conjunction with various governmental agencies to appraise the salinity sources in the basin and to evaluate the future impact of water resource developments on mineral water quality. The results pertaining to the Grand Valley in particular indicated the salt pickup to be about 18 metric tons per hectare per year, which is the result Hyatt (1970) established for the 1963-1968 years. Both of these references are useful data sources for examination of the Upper Colorado River System. Also, both studies utilized salinity data collected by the Federal Water Pollution Control Administration (now the U. S. Environmental Protection Agency).

One examination of the sources of salinity in the basin reveals that of man-made contributions, irrigated agriculture has the largest effect. Consequently, the major aspect of salinity control in the region must be the effective

use of irrigation diversions by improving the efficiency of conveyance, farm, and wastewater systems. One of the several important efforts funded by the U. S. Environmental Protection Agency to develop salinity control technology is the Grand Valley Salinity Control Demonstration Project in western Colorado. The reason for selecting Grand Valley for intensive study is because the annual salt pickup per acre is greater in this particular irrigated area than any other irrigation system in the Upper Basin.

The primary source of salinity in the Grand Valley is from the extremely saline aquifers overlying the marine-deposited Mancos shale formation. The shale is characterized by lenses of salt in the formation which are dissolved by water from excessive irrigation and conveyance seepage losses when it comes in contact with the Mancos shale formation. The introduction of water from these surface sources percolates into the shallow groundwater reservoir where the hydraulic gradients displace some water into the river. This displaced water has usually had sufficient time to reach chemical equilibrium with the salt concentrations of the soils and shale. These factors also make the Grand Valley an important study area, since the physical conditions encountered in the valley are common to many locations in the Upper Basin.

HYDRO—SALINITY MODEL

In this section, a summary of the inflow-outflow analysis and results from the hydro-salinity model will be presented. Inflows to the Grand Valley occur as flows in the Colorado River, Gunnison River, and precipitation. In addition, a small quantity of water is imported for domestic and industrial purposes, and a possibility exists that precipitation on the watershed adjacent to the valley may contribute via diffuse groundwater inflows. Neither of these latter flows are deemed significant, especially the inflow from surrounding lands because of the low annual precipitation (200-250 mm) and high evaporative demands (1000-1100 mm).

As a means of better identification, data for the 1968 water year from the U. S. Geological Survey (USGS) and U. S. Weather Bureau can be utilized (Table 3). Inflows passing the USGS gaging stations "Colorado River near Cameo" (297, 523 ha-m), "Plateau Creek near Cameo" (13,810 ha-m), and "Gunnison River near Grand Junction" (178,045 ha-m) totaled 489,378 ha-m carrying an estimated salt load for 1968 of 2,787,400 metric tons. The outflows passing the station "Colorado River at Colo-Utah State Line" totaled 458,923 ha-m and approximately 3,423, 314 metric tons of salt. These figures represent either published data or interpolations thereof. A comparison of the inflows and outflows indicates that 30,458 ha-m of water were depleted from the system and 635,914 metric tons of salt added.

The second approach to establishing the effects of water use in the Grand Valley is to model the complex inter-relationships associated with irrigation and drainage. Several parameters are added to the analysis to account for the various flows which take place.

The first segment encountered is the delineation of the canal diversions. As the water is diverted from the rivers into the canals and ditches, a certain portion of the flow seeps underground or evaporates from the conveyance surfaces, while still another fraction is spilled into wasteways as a means of regulating flow. The remainder of the flow is diverted through small headgates into an extensive lateral system leading to the fields. It is important

in this type of analysis that each flow path be defined, because each results in a different salinity effect. For example, the evaporative losses concerntrate the salts in the remaining flows, whereas the seepage enters the saline groundwater basin and results in salt pickup.

Westesen (1974) examined the 1968 water year in some detail and combined many of the principles discussed by Walker (1970) into an accounting of the flows derived for irrigation in the Grand Valley. His results, shown in Tables 4 and 5, compare very well with data collected by the authors in recent years.

Much of the local water table problems are due to over-irrigation, especially along the higher northern lands in the area. Lower areas and isolated trouble spots are affected by excessive groundwater flows reaching the ground surface. If the local canals and laterals were lined (including farm head ditches), Table 4 indicates that 9,494 ha-m annually, which amounts to

TABLE III

Grand Velley water budget for 1968 water year

Budget Item	*hectare-meters*
Surface inflows	
Colorado River near Cameo, Colorado	297,523
Plateau Creek near Cameo, Colorade	13,810
Gunnison River near Grand Junction, Colorado	178,045
Total	489,378
Effective precipitation	
Cropland	3,083
Phreatophytes	666
Total	3,749
System depletions	
Water surface evaporation	
Canals	986
Rivers	987
Phreatophyte consumption	
Along canals and drains	7,891
Adjacent to rivers	2,639
Cropland consumption	21,701
Total	34,204
Surface outflows	
Colorado River at Colorado-Utah State line	458,923

TABLE IV

Grand Valley distribution of canal flows in 1968

Budget item	*Hectare-meters*
Canal diversions	
Spillage	12,699
Seepage	3,083
Evaporation	987
Lateral diversions	52,279
Total	69,048
Lateral diversions	
Seepage	6,288
Field tailwater	19,975
Root zone diversions	26,016
Total	52,279
Root zone diversions	
Evapotranspiration	18,495
Deep percolation	7,521
Total	26,016
Ground-water return flows	
Phreatophyte consumption	7,398
Subsurface and drain flows	9,494
Total	16,892

55 per cent of the groundwater inputs, would be prevented from contributing to local drainage problems. (If only the canals were lined, the groundwater would be decreased by only 18 per cent.) Such improvements may also reduce the evapotranspiration from phreatophytes and result in significant water savings as well. Canal linings appear to be the initial program for controlling salinity in the Grand Valley although it is the least effective alternative available.

Probably the greatest potential for salinity control lies in on-farm water management which directly includes the lateral conveyance system. Together, deep percolation and lateral seepage contribute 82 per cent of the groundwater flows. If effective irrigation scheduling programs are incorporated locally, which means accompanying the scheduling services with rehabilitation of the irrigation systems, the need for field drainage will be diminished.

Thus, the first steps in a salinity control program are to minimize : (a) deep percolation losses from croplands (ideally, the deep percolation losses

TABLE V

Salt budget for Grand Valley during 1968

Budget item	*Flow (ha-m)*	*Cancentration (mg/l)*	*Salt load (metric tons)*
Inflows			
Colorado River near Cameo	297,523	454	1,352,622
Plateau Creek near Cameo	13,810	454	62,638
Gunnison River near Grand junction	178,045	769	1,372,140
Total			2,787,400
Outflows			
Colorado River near Colo-Utah State line	458,923	745	3,423,314
Salt pickup			635,914

would not exceed the leaching requirement), and (b) seepage losses from canals and laterals. By minimizing the amount of flow reaching the groundwater, the requirements for field drainage will also be minimized. As higher levels of salinity reduction are sought, field drainage becomes a more feasible component of a valley-wide salinity control program.

The results to date clearly show that the *key* to reducing the salt load contribution to the Colorado River from Grand Valley is improving on-farm water management practices in order to minimize deep percolation losses and consequent salt pickup.

SOIL CHEMISTRY MODELING

The hydro-salinity model describes the present situation in the study area regarding water and salt flows. However, the only method for predicting the reduction in salts returning to the river through implementation of any salinity control measure(s) is by assuming a one-to-one relationship between water and salt. That is, if the subsurface return flow is reduced by 50 per cent the salt is also reduced by 50 per cent. In order to overcome this limitation, a project "Irrigation Practices, Return Flow Salinity, and Crop Yields" was initiated.

One of the primary objectives of this research is to model the transport of salts in the soils in this area. The first portion of the flow of water and consequent transport of salts is through the root zone which is usually a zone of unsaturation. A numerical model of the moisture flow and chemical and biological reactions occurring in the root zone has been developed

by Dutt, et al. (972). This is the basic model which has been used in this study to describe the salt transport being observed in the field.

The model consists of three separate programs. The first program describes the soil moisture movement and distribution with time. The second program interfaces the soil moisture movements with the chemical-biological model. This is needed because the horizons used in the calculations of soil moisture and chemistry differ. The third program computes the chemical and biological activity occurring in the soil profile.

Preliminary studies have been made with this model to evaluate its capabilities and to insure compatibility with the available computer facilities. Analysis of 1975 field data allowed extensive testing of the model. Modifications have been made to more accurately describe existing field conditions. From these data, equations have been developed to predict the variation in chemical quality (including ionic constituents) of the moisture movement through the soil profile, as well as the salt pickup resulting from movement of subsurface irrigation return flows over the Mancos shale beds. These results combined with the hydro-salinity model will allow an evaluation of various salinity control measures upon salinity reaching the Colorado River.

EVALUATION OF SALINITY CONTROL MEASURES

The principal study area in Grand Valley, which has been used for evaluating the effectiveness of canal and lateral lining, as well as irrigation scheduling and tile drainage, in reducing the salt load entering the Colorado River, is now being used as a demonstration project beginning in February, 1974. The advantage in continuing to utilize this study area is that the hydrology is already known. In addition, there has been considerable expenditure of funds in both equipment and personnel for instrumenting this particular 1,876 ha demonstation area. The wealth of available information provides a strong basis for evaluating the effectiveness of salinity control measures.

A variety of irrigation methods are being demonstrated, including "tuning up" present irrigation methods being used in the study area. Considerable experience has been gained in improving the existing irrigation methods while evaluating irrigation scheduling as a salinity control measure in Grand Valley. However, more advanced irrigation methods are just now being evaluated as to salinity control benefits in Grand Valley. The irrigation systems that have been constructed under this project include automated farm head ditches, border irrigation, sprinkler irrigation, and trickle irrigation.

The most significant aspect of this particular demonstration project is the employment of a salinity control technology "package", rather than a single control measure. Experience in Grand Valley has shown that the most significant progress is made when the gamut of questions can be answered regarding the interrelationships between water management and agricultural production. Thus, the concept of a technology package, along with an understanding of the "system" including other agricultural inputs, provides the necessary base for providing sould advice to the farmer, which in turn facilitates the development of credibility and consequently farmer acceptance.

COST EFFECTIVENESS ANALYSIS

The currently funded EPA research project, "Irrigation Practices, Return Flow Salinity, and Crop Yields," which is nearing completion in Grand

Valley, will be utilized in developing the cost-effectiveness of each salinity control measure. In addition, the results from the research project will provide valuable information regarding increased crop yields that can be expected from improved water management practices. The combined results of the research project and the demonstration project are extremely important in establishing the benefits to be derived from implementing a total program of salinity control.

The results from both projects, which will integrate eight years of concentrated study in the valley, will serve as a basis for an action salinity control program. Such a program would detail the optimal strategy for implementing various levels of individual salinity control measures into a comprehensive technology package. To develop this kind of policy, cost-effectiveness functions relating the reductions in the system salt loadings resulting from a specified investment would be individually assessed in an optimizational format to arrive at the least cost combination for achieving a desired level of salinity control. The analytical procedures being used to determine the optimal combinations of salinity control technologies are described by Walker (1976).

An illustration of these procedures considering only two of the potential salinity control alternatives will serve to demonstrate these anticipated research results in the Grand Valley. The first alternative is concrete lining of the local irrigation conveyance system in order to reduce seepage and thereby partially alleviate salt loading. Hydrosalinity analyses in the valley have delineated the seepage contribution from the twelve major canal and ditch segments and the network of small channels or laterals serving between major carriers and the croplands. When coupled with cost information supplied by the local office of the Bureau of Reclamation it is possible to express salt pickup reductions in terms of lining costs over the range of possible implementation. This procedure, therefore, formulates cost-effectiveness relationships for each conveyance segment. These can be systematically compared to determine the optimal policy for their incorporation into a valley-wide conveyance lining program. Walker (1976) made such an analysis as shown in Figure 4, which itself is a "second level" cost-effectiveness function descriptive of conveyance lining in general for the area. The results in Figure 4 are of two types. First, the upper curve or boundary represents the minimum cost (ordinate) associated with alleviating a specified level of salt pickup (abscissa). And secondly, the strategy for accomplishing this minimum cost is traced by noting the vertical distribution of investments for each conveyance segment. For example, if salinity were to be reduced by 200,000 metric tons annually, it would require an estimated annual expenditure of about $ 1,000,000; about 60 per cent of which should be made in improving the farm head ditch lateral system and 40 per cent in improving the conveyance laterals. At this level of control, no investments into alternative canals, ditches, or laterals would be "optimal."

The second salinity control alternative considered herein is desalination of brackish groundwater and/or drainage waters. Utilizing cost estimating procedures for various desalting systems published by the office of Saline Water and Bureau of Reclamation, Walker (1976) determined the costs of removing salts in the valley by this method. Desalting costs were then compared to the channel lining costs (Figure 4) and a combined cost-effectiveness

function was developed (Figure 5). Again the upper curve represents the minimal costs and a vertical cut delineates the optimal strategy.

It should be emphasized that Figures 4 and 5 include only two of the many possible salinity control alternatives and are presented herein to illus-

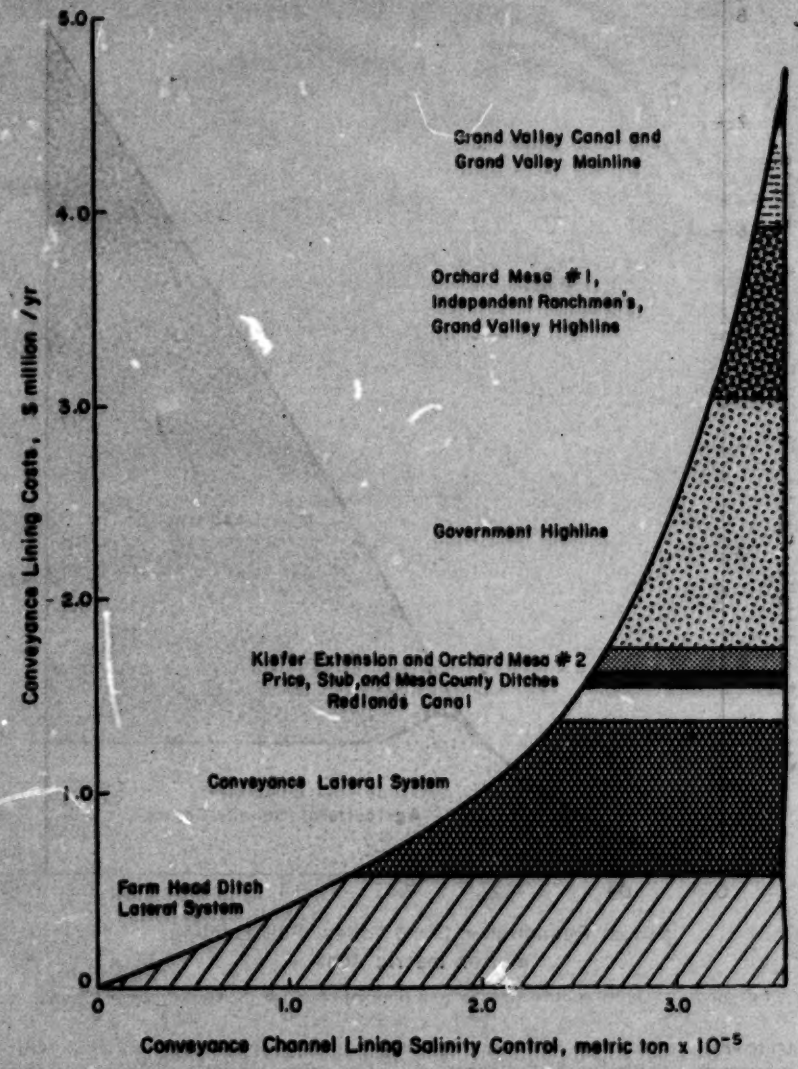

FIGURE 4 : Optimal conveyance channel lining policy for the Grand Valley irrigation system

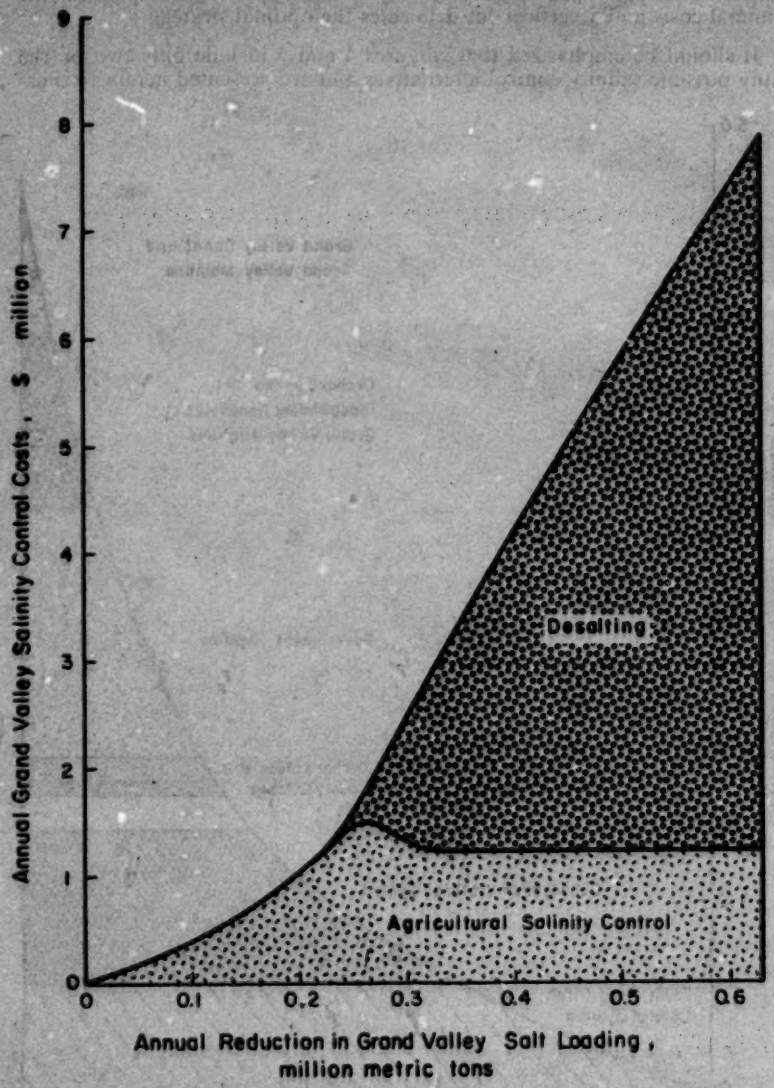

FIGURE 5 : Salinity control strategy and optimal costs for the Grand Valley example

trate the concept of selecting optimal policies. The final analyses will incorporate the remaining alternatives. The value of such an analysis might be demonstrated by comparing the optimal results in Figure 5 with the alternative of exclusively lining the distribution system. Suppose a planner

without the benefits of this kind of analysis decided that to reduce local salt loading by 350,000 tons, he would recommend a comprehensive lining program involving nearly all of the valley's conveyance systems. On an annual basis, his costs would be about $4·3 million, or about 30 per cent higher than the costs shown in Figure 5 for the same level of salinity control.

Since salinity control in Grand Valley must evolve with the development of water resources in the Upper Colorado River Basin, this work will describe the time-varying characteristics of salinity control strategies, point out the relative advantages of alternative measures, and illustrate how the optimal combination of alternatives might be determined. As other critical regions require salinity management, these reports could serve as a guide in illustrating the process necessary in delineating cost-effective strategics for alleviating water quality degradation from irrigated agriculture.

SUMMARY AND CONCLUSIONS

There are a variety of water quality problems resulting from irrigated agriculture. The most commonly encountered problm is waterlogging and salnity; however, sediment from surface runoff is also a serious problem in some irrigation systems. Other water quality problems that have been noted are eutrophication resulting from the transport of phosphates and nitrates from agricultural enterprises, as well as the transport of pesticides.

Research has shown that water quality degradation can be alleviated by adopting improved irrigation water management technologies. However, an effective program for improving water quality will usually require a combination of appropriate technologies.

In studying any particular irrigation system, the first step is identifying the extent of water pollution problems. This is usually accomplished by analyzing inflow-outflow data for the irrigated area. Then, the sources of these pollutants must be established, which may require extensive field investigations. This requires some form of hydroquality of flows within the irrigation system. Afterwards, appropriate technologies can be delineated for either reducing the sources of pollutants, or treatment to remove the pollutants.

The next step is a cost-effectiveness analysis, where the cost of implementing a technology to various levels (e.g., lining those sections of canals with the highest seepage rates, or lining all of the canals) is compared against its effectiveness for improving water quality. Either direct or indirect measures of effectiveness might be used. For example, for an area having waterlogging and salinity problems, groundwater levels might be used as an indirect measure of effectiveness, which requires that the relationship be known between groundwater levels and groundwater salinity, or soil salinity, whichever is the goal.

A cost-effectiveness relation must be developed for each appropriate technology. In some cases, cost-effective relations must be developed for combinations of technologies, where the total effectiveness of the combination is greater than the sum of the individual technologies. These cost-effectiveness relations can then be assessed in an optimizational format to arrive at the least cost combination for achieving a desired level of water pollution control.

These concepts were illustrated for three irrigation systems in the western United States; namely, Yakima Valley, Wellton-Mohawk Irrigation and Drainage District, and Grand Valley. These case study areas represent a wide variety of water quality problems resulting from irrigated agriculture.

Yakima Valley has problems primarily with sediment and nitrogen, which require an analysis of surface and subsurface return flows, respectively. The cost-effectiveness analysis was used both for comparing various technological alternatives and policies for implementing appropriate technologies.

Since salinity is the primary water quality problem in the Wellton-Mohawk Irrigation and Drainage District, any cost-effectiveness analysis must be capable of predicting changes in subsurface return flows. The data analysis compared on-farm improvements with desalting.

The Grand Valley is also an area where the key is minimizing subsurface return flows (e.g., minimize canal and lateral seepage, and deep percolation losses from over-irrigation). The cost-effectiveness analysis provides the optimal technological strategy for reducing the salt loads from the Grand Valley.

The increasing emphasis upon the environment, and more recently the emphasis upon irrigation return flow quality control, has led to the undertaking of the case studies reported herein. Only in recent years have such studies been undertaken, but they will become more common in the future.

Even after taking into account the "site specific" nature of irrigated agricultre in general, and these case studies in particular, the most cost-effective solutions for reducing water quality problems from irrigated agriculture will likely result from improved on-farm water management practices.

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